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Vertical Temperature Structure During the 1966 Thanksgiving Week Air Pollution Episode in New York City

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ABSTRACT—This paper presents time cross-sections of vertical temperature structure during the 1966 Thanksgiving week air pollution episode in New York City, based on 6-hourly soundings at Kennedy Airport. The analyses depict numerous inversions in the lower 10,000 ft of the atmosphere, including an interesting sequence of surface-based inversions and an outstanding inversion aloft. Diurnal and daily variations in the height of the mixing layer can also be seen. Some possible influences of the vertical temperature structure on SO_2 concentrations in Manhattan are discussed, and it is suggested that exceptional peak SO_2 concentrations were largely due to the fumigation process.

1. INTRODUCTION

During Thanksgiving week of 1966, much of the eastern United States was dominated by an anticyclone of the type that in past decades would have been associated with pleasant weather. In recent years, however, such systems have often been accompanied by objectionable concentrations of air pollutants in urban areas. In the metropolitan area of New York City, SO_2 concentrations reached alarming levels especially from November 23 to 25. Figures 1 and 2 show hourly average concentrations during the week (Thanksgiving was the 24th). These concentrations are summarized in table 1 (SO_2 concentrations were measured continuously, using the conductometric method, by the New York City Department of Air Pollution Control at their Manhattan Laboratory, 121st St. and Lexington Ave.). These values are indeed high, particularly compared to the National Primary Air Quality Standards for sulfur oxides as set by the Environmental Protection Agency (1971):

> Maximum 24-hour average concentration not to be exceeded more than once a year, 14 pphm (parts per hundred million, by volume).
> Annual arithmetic mean concentration, 3 pphm.

Criteria for sulfur oxides standards have been published by the U.S. National Air Pollution Control Administration (1969). During November 23–25, the average SO_2 concentration in metropolitan New York City was more than *three times* the 24-hr standard! In connection with this episode, Glasser et al. (1967) concluded that 24 excess deaths per day occurred in New York City during Nov. 23–29, 1966. On no day of this particular week were there fewer than 254 deaths. This was the only 7-day period from November 1 through December 10 in 6 yr (1961–66) during which this was true.

TABLE 1.—*Average SO_2 concentrations (pphm) for the Nov. 20–26, 1966, air pollution episode*

Date	20	21	22	23	24	25	26
Highest 1 hr	34	48	48	69	97	102	40
24 hr	16	19	25	51	47	41	16
Lowest 1 hr	8	8	9	30	18	17	6

Meteorological information and additional air quality data on this episode have been given by Fensterstock and Fankhauser (1968). The purpose of the present paper is to document the vertical temperature structure over New York City (i.e., as actually measured from Kennedy Airport) and to infer likely influences on SO_2 concentrations. The analyses of temperature structure are based on rawinsonde observations of temperature and wind at 6-hr rather than the usual 12-hr intervals. The rawinsonde temperature sensor is a thermistor with a lag constant (i.e., the time required for the sensor to respond to 63 percent of the interval between an initial and a final stable temperature) of no more than 6 s in the lower 10,000 ft. [The lag increases with height (Ference 1951).] Since the rawinsonde ascends at around 1,000 ft/min, the sensor detects 63 percent of an instantaneous temperature change in roughly 100 ft. The effect of this lag on temperature accuracy depends, of course, upon the actual temperature variation with height. Thus, it is clear that rawinsonde-reported temperatures only describe relatively gross features of the vertical temperature structure

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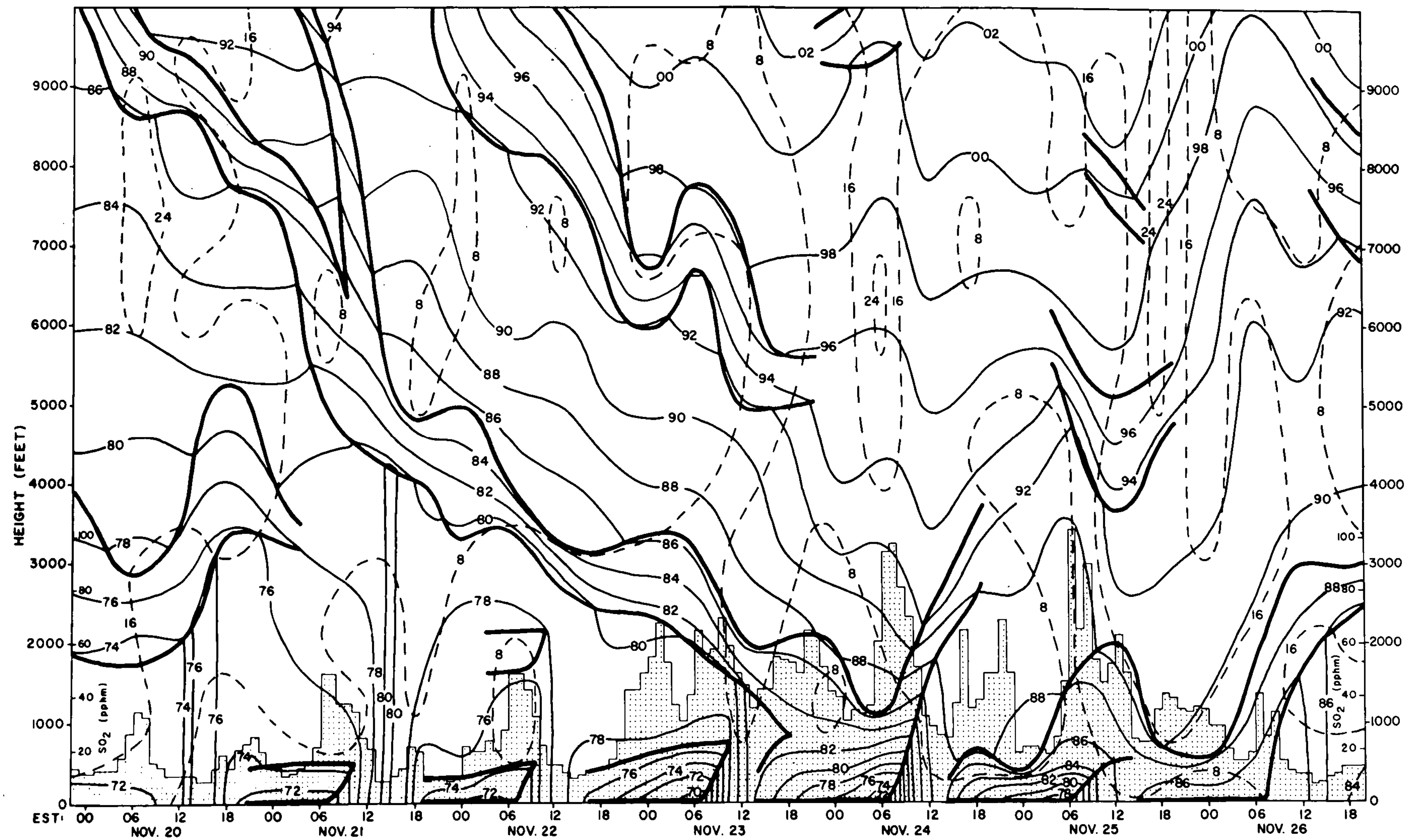

FIGURE 1.—Average hourly SO_2 concentrations (stippled area) in parts per hundred million (pphm) in Manhattan, New York City, and time cross-section of potential temperature based on 6-hourly rawinsonde flights at John F. Kennedy International Airport. Potential temperature isotherms (thin lines) are in degrees Kelvin with the initial digit omitted (e.g., 76=276° K). Wide lines depict base or top of an *actual* temperature inversion or isothermal layer (fig. 2). Isovels (dashed lines) are in knots.

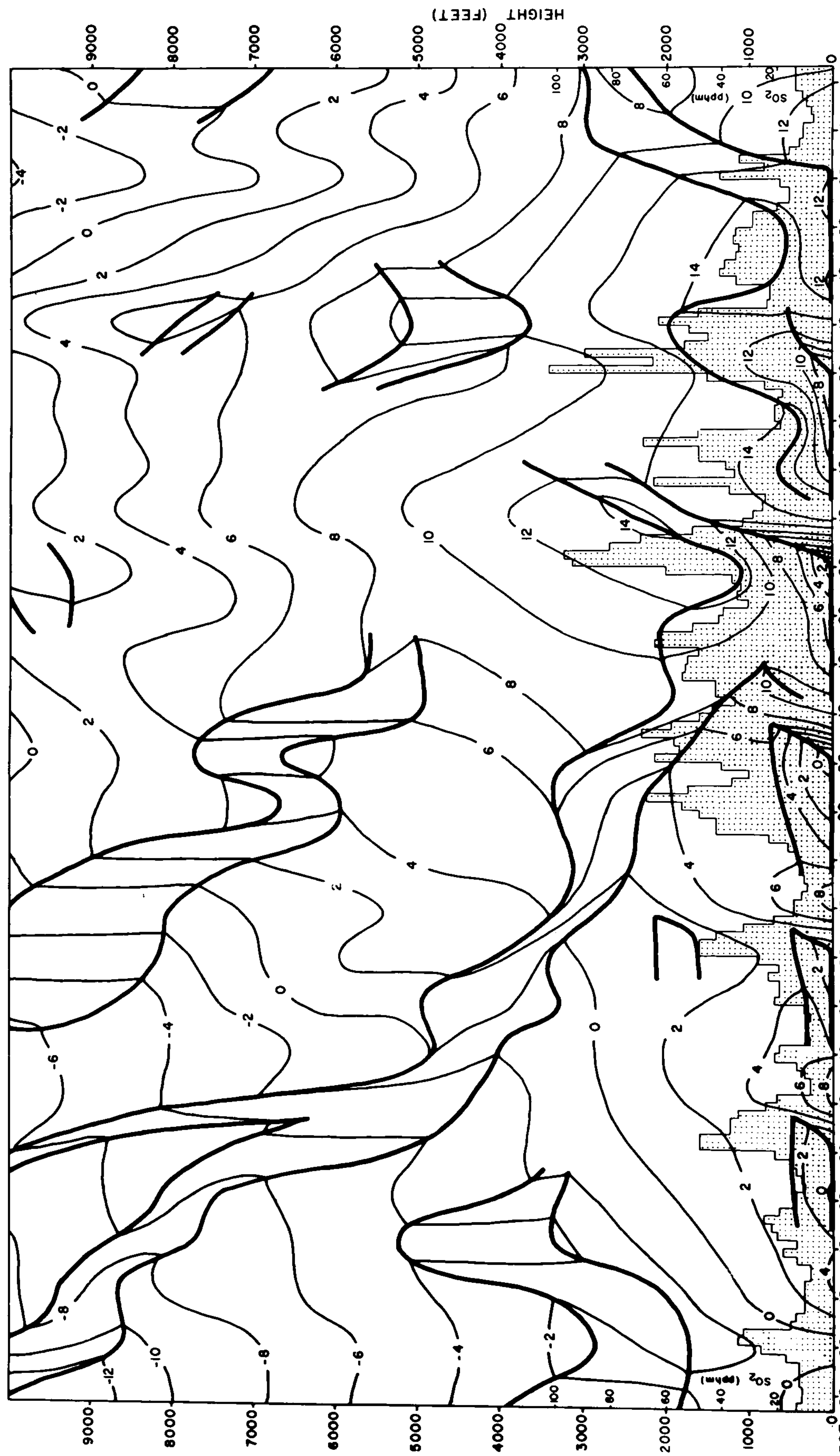

FIGURE 2.—Same as figure 1 except isotherms are of *actual* temperature (°C).

2. DISCUSSION

Figure 1 shows the time cross-section of wind speed and potential temperature. The latter is particularly suited to depiction of well-mixed surface layers and subsidence aloft. Figure 2 is in terms of *actual* temperature, which clearly shows the base and top of isothermal or inversion layers. These analyses are based on upper air data obtained from routine National Weather Service (NWS) rawinsonde flights launched from John F. Kennedy International Airport, 14 mi southeast of the SO_2 monitoring station in Manhattan. Complete rawinsondes were released every 6 hr at 0015 EST, 0615 EST, etc. Airways weather observations at Kennedy Airport were also used in the analyses. The analyses fit all data.

The synoptic weather situation during this air pollution incident may be seen by referring to the Daily Weather Maps (American Meteorological Society 1967). Briefly, from midday of November 20 through November 24, New York City was close to the center or the ridge line of a slow-moving polar-continental anticyclone; only high clouds, mostly scattered, were reported, and surface wind speeds only occasionally exceeded 6 kt. On the 25th, a short-wave cyclone moved northeastward through the Great Lakes; its only effect at New York City seems to have been to increase the wind speeds slightly. On the morning of the 26th, a cold front accompanied by showers passed New York from the north and brought a noticeable improvement in air quality.

Figures 1 and 2 show clearly that during Thanksgiving week the lower 10,000 ft of the atmosphere over New York City contained numerous temperature inversions. Most soundings detected at least two. These inversions were of varying intensity and duration and occurred at several heights. A particularly interesting inversion appeared near 10,000 ft early on November 20 and clearly maintained its identity as it migrated downward to merge with the surface-based inversion during the night of November 23–24. Evidence of subsidence is shown by the slope of the isentropes in and immediately above this inversion (fig. 1). In addition, subsidence was indicated by a lack of warm air advection at New York City on the 850- and 700-mb charts and by the vertical distributions of mixing ratio. According to the cross sections, the inversion subsided 9,000 ft in 4 days, averaging about 3/4 cm/s. The temperature at 2,500 ft increased 17°C from November 20 to 24. The inversion near 3,000 ft at the end of the cross sections represents the cold front that passed at the surface around 0700 EST on November 26. As is also common in slow-moving anticyclones, the wind speeds were generally light (fig. 1). Only near the beginning and ending of the episode did the speeds below 4,000 ft exceed 16 kt.

Figures 1 and 2 show that at Kennedy Airport a surface-based inversion occurred every night during the period except November 19–20. The intensity of these inversions increased noticeably on successive nights through the 24th when the inversion aloft joined the surface inversion. Another interesting feature of the cross sections is the rather early afternoon hour at which a surface-based inversion seems to have formed on November 23, 24, and 25.

As has been shown by Hosler (1961), low-level (surface-based) inversions are common at night in most nonurban regions of the United States. On the other hand, DeMarrais (1961) has shown that at night in the more built-up parts of cities the atmosphere in the lower few hundred or so feet is usually much less stable (sometimes superadiabatic) than in the nearby countryside, and the unstable city layer is frequently overlaid by a stable layer. This urban stable layer aloft appears continuous with the part of the rural inversion that is at about the same elevation. Such conditions in the vicinity of Cincinnati, Ohio, have been documented by Clarke (1969) and, in the vicinity of New York City, by Davidson (1967) and Bornstein (1968). From his rather detailed study of the urban heat island effect in New York City, Bornstein (1968) concluded that the nature of the Kennedy Airport synoptic soundings (rawinsondes) is nonurban because of the relatively high frequency of surface inversions at 0615 EST. Thus, in considering relationships between SO_2 concentrations and vertical temperature structure, the analyses of temperature soundings at Kennedy Airport that depict surface-based inversions should be interpreted in terms of the expected temperature structure over Manhattan where the SO_2 measurements were made. Under these conditions, it may be assumed, therefore, that over central New York City there was a comparatively unstable (nearly adiabatic) "mixing layer," not as deep as the surface-based inversion, with a more stable layer immediately above. This interpretation can be made only in very general terms since in detail the temperature structure may vary considerably over different parts of the city.

In the daytime, typical unstable conditions in the surface boundary layer over Manhattan were not considered significantly different from those at Kennedy Airport. As depicted in figures 1 and 2, nocturnal, low-level inversions were weakened and usually eliminated during the morning as the atmosphere was heated from below. Similarly, over the urban area, the stable stratum topping the shallow nocturnal mixing layer was probably weakened and eliminated during the day. The vertical redistribution of heat absorbed by the surface was assumed to result in nearly dry-adiabatic conditions (shown in fig. 1 as regions where the potential temperature is practically constant with height).

To gain insight into the effects of the vertical temperature structure on SO_2 concentrations during this episode, we must first consider the normal diurnal variations of SO_2 concentrations and their assumed causes. In this regard, one must realize that the sort of diurnal variation in vertical temperature structure that has just been described is not unusual for New York City, although for much of the Thanksgiving episode the degree and duration of low-level stability was exceptional.

The 1957–64 annual mean SO_2 concentrations on an hourly basis at the Manhattan Laboratory may be summarized as follows:

Early morning minimum of 13 pphm during 0100–0500 EST.
Morning maximum of 25 pphm during 0700–0900 EST.
Afternoon secondary minimum of 15 pphm during 1300–1700 EST.
Evening secondary maximum of 18 pphm during 1800–2200 EST.

The early morning minimum concentration is attributed (1) to minimal emissions during early morning hours (Davidson et al. 1969) and (2) to the frequent occurrence at night of low-level stable layers that "trap" pollutant plumes aloft, especially plumes from elevated sources or hot plumes that rise into the stable layer because of their buoyancy. Direct evidence of SO_2 plumes within and between low-level inversions over New York City has been given by Davidson (1967) based on helicopter measurements. The morning maximum concentration is presumed to result from (1) an increase in emissions near the start of the normal workday and (2) transport of higher level trapped pollutants to the surface by convectively induced mixing after sunrise. Davis and Newstein (1967), reporting on tower measurements during two SO_2 pollution episodes in Philadelphia (one episode included Thanksgiving 1966), concluded that peak SO_2 concentrations occurring at ground level a few hours after sunrise seemed to be associated with the fumigation process described. They also found higher SO_2 concentrations aloft in inversion conditions than at the surface. The afternoon secondary minimum concentration is attributed largely to the typical afternoon maximum of dispersion (i.e., faster winds and deeper mixing layers) and to somewhat reduced emissions with respect to the morning "start-up" period. The evening secondary maximum concentration reflects a decrease in dispersion from the afternoon maximum and perhaps a slight increase in those SO_2 emissions associated with domestic activities.

The general features of the normal diurnal variation of SO_2 concentrations at Manhattan can be seen in figure 1 or 2, although the episode concentrations usually were greater than normal and some features were distorted, probably due to factors not considered here. On the morning of November 20, no surface-based inversion was present and the lapse rate was nearly adiabatic to about 1,800 ft (fig. 1). At that time the winds were comparatively brisk, 16 kt near 500 ft and about 12 kt at the surface. Thus, the SO_2 peak around 0700 EST appears due primarily to increased emissions at the start of the day. After the morning peak, the SO_2 concentrations remained comparatively low through the afternoon, probably reflecting the effect of increased vertical mixing that reached 3,000 ft by 1700 EST. This effect seems to have been offset to some extent, however, by slower wind speeds. The secondary maximum concentration in the evening of November 20 was rather broad, as is often the case.

During the middle of the night of November 20–21, the low SO_2 concentrations were due, presumably, to a decrease in emissions, especially those from sources near ground-level. Emissions from elevated sources, or emissions with significant buoyancy (e.g., large emitters operating around the clock), probably remained aloft, constrained by the stable air there. Thus, on the morning of November 21, the peak concentration was higher and high values lasted longer than on the previous morning. We believe that this was due largely to the fumigation process. Low afternoon concentrations were associated with vertical mixing through more than 4,000 ft. During the remainder of November 21, SO_2 concentrations followed the established pattern.

On November 22, until about midafternoon, the SO_2 concentrations were very much like those for similar hours of the previous day. The features of low-level temperature and wind structure were similar also, although vertical mixing in the afternoon only reached 2,800 ft, the base of the subsiding inversion.

On the evening of November 22, the typical secondary concentration peak was obscured by a buildup to 67 pphm during 0100–0200 EST on the 23d. The reason for this occurrence is not apparent, although the surface-based inversion was much more intense than on previous nights. This anomalous peak concentration seems also to have distorted the normal early morning minimum concentration. Thus, just before sunup on the 23d, surface SO_2 concentrations were already high. The ensuing, even higher, concentrations during the 0600–1000 EST period appear to have resulted from the normal diurnal increase in low-level emissions *and* from mixing down to the ground of SO_2 that had been trapped aloft. As the mixing height increased beyond the top of the low-level inversion, relatively uncontaminated air was briefly introduced and was in part responsible for the decrease in concentration to 35 pphm during the 1300–1400 EST period. The anomalous high concentrations during the remainder of the afternoon and through the evening of November 23 seem to have been influenced by the very low mixing heights that were caused by the subsiding inversion aloft and by the early afternoon development of additional low-level stability (e.g., the surface-based inversion at Kennedy Airport beginning about 1400 EST).

During the night of November 23–24, low-level stability reached exceptional values as the subsiding inversion amalgamated with developing stable conditions near the ground at Kennedy Airport. Thus, at 0600 EST on November 24, conditions were highly favorable for trapping emissions aloft. Following sunrise, SO_2 concentrations first increased rapidly to a peak of 97 pphm during 0700–0800 EST and then decreased to 24 pphm during 1400–1500 EST as the mixing height increased to 2,000 ft. It is interesting that, on November 24 between 0600 and 1800 EST, what appears to be the remains of the subsidence inversion ascended before it disappeared.

Sulfur dioxide concentrations during the first several hours of November 25 fell to almost normal values. They were followed at 0600–0700 EST, however, by the highest hourly value of the episode, 102 pphm. As during the preceding morning, this exceptional concentration may be ascribed largely to the fumigation process and to an increase of emissions. An additional contributing factor could have been the comparatively slow rate at which the mixing height increased after sunrise. Following the morning maximum on the 25th, the concentrations de-

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clined but remained around 50 pphm until after 1400 EST. This was attributed largely to the extremely low afternoon mixing height of 500 ft, which at least temporarily seems to have more than offset wind speeds of 8–12 kt within the mixing layer.

On the afternoon of November 25, a cloud ceiling formed at roughly 10,000 ft, and widely scattered light prefrontal rain showers began in the vicinity of New York City at about 2100 EST. These showers lasted until the cold front passed at 0700 EST on the 26th. As shown in the cross sections, the frontal inversion merged with the surface-based inversion. The comparatively low peak concentration at the time of the frontal passage was of brief duration, due to the brisk winds and very rapidly increasing mixing height in the fresh air mass.

3. SUMMARY AND CONCLUSIONS

Based on 6-hourly soundings at Kennedy Airport, this paper has documented the vertical structure of potential and actual temperature during the 1966 Thanksgiving week air pollution episode in New York City. During this period, the lower 10,000 ft of the atmosphere contained numerous inversions. Of particular importance, in terms of atmospheric dispersion, were the low-level inversions (i.e., at the surface at Kennedy Airport) that occurred every night except the first day of the week and that, at the peak of the pollution episode, formed early in the afternoons and attained considerable intensities. Another interesting feature of the cross sections was a significant inversion aloft, apparently associated with subsidence. In 4 days this inversion descended 9,000 ft and on the night before Thanksgiving merged with the surface inversion to produce a high degree of stability through a layer more than 2,000 ft thick.

The cross sections also show hourly average SO_2 concentrations in Manhattan that reached alarming levels. We suggest that the peak SO_2 concentrations occurring soon after sunrise are due largely to the fumigation process. This is not meant to imply that other factors are unimportant in explaining the variations of SO_2 concentration. For example, there can be little doubt about the significance of airflow patterns. However, under light wind conditions, the airflow in New York City is always complicated (Davidson 1967) as in many cities, and available wind data are insufficient to define such details for the episode.

Cross section analyses such as shown here obviously can be of great use in monitoring and forecasting atmospheric dispersion and air quality and as a basis for emergency control actions, especially during stagnation conditions. However, sufficiently detailed and reliable cross sections are critically dependent upon timely meteorological soundings. Fortunately, the provision of such soundings is a major function of the Environmental Meteorological Support Units that are being established in many major United States cities by the NWS (Kirschner 1970).

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